A Novel Dual Wavelength Optical Beam Attenuation Meter for Automated Underwater Vehicles (SAM)

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LONG TERM GOALS

Several compact sampling platforms have recently been developed or are gaining widespread use in Naval operations and oceanographic research. In addition to limited sensor payloads, many of these platforms are autonomous and intended for extended deployments. Sensors compatible with these platforms must therefore be compact, low power, and able to accommodate effective anti-biofouling measures. Developing optical sensors with these qualities for use in Naval operations and oceanographic research is a core long term goal.

Beam attenuation is of particular interest because it is a fundamental Inherent Optical Property used in many Naval applications, including estimates of diver visibility and vulnerability, and predicting the performance of optical MCM identification systems. Attenuation is also widely used in determining particle concentration, particle composition, and water clarity.

OBJECTIVE

Our core objective is to design, construct, and characterize a beam attenuation meter compatible with compact and remotely deployed sampling platforms. Measurement accuracy should be comparable to conventional beam attenuation meters. The device should have a hydrodynamic flat sensing face and a remotely sensed sample volume to avoid having to pump water. Another objective is to integrate this sensor into AUVs such as the Slocum glider.

APPROACH

Briefly, a technique for determining beam attenuation has been developed where two measurements of backscattering are made, each with the same angular weighting function, but over different pathlengths (distance from source to sample volume to the detector). In the simplest theoretical case of collimated source and detector beams, the beam attenuation coefficient is derived from the ratio of scattered fluxes measured by the detectors (β_{m1} and β_{m2}):

$$c = \ln\left(\frac{\beta_{m1}}{\beta_{m2}}\right)(l_2 - l_1)^{-1}, \qquad (1)$$

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<tr><td colspan="7">14. ABSTRACT
Several compact sampling platforms have recently been developed or are gaining widespread use in Naval operations and oceanographic research. In addition to limited sensor payloads, many of these platforms are autonomous and intended for extended deployments. Sensors compatible with these platforms must therefore be compact, low power, and able to accommodate effective anti-biofouling measures. Developing optical sensors with these qualities for use in Naval operations and oceanographic research is a core long term goal.</td></tr>
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where l_1 and l_2 are the respective pathlengths for each scattering measurement. An advantage of the method is that attenuation is obtained ratiometrically. Thus, the method is self-calibrating with respect to fluctuations in source intensity and does not require the respective gains of the detectors be known.

The method has several advantages over standard attenuation meters: 1) form factors for a sensor employing this technique can be small (cm's); 2) a hydrodynamic, flat sensing face may be used; 3) a pump is not required; 4) anti-biofouling measures such as copper shutters are readily integrated; and 5) low powered lasers may be used that reduce power requirements. The sensor employing this method is a Scattering-Attenuation Meter (SAM).

Through the 6 month Phase I period and the first 12 month period of Phase II, our approach has been to evaluate the performance of the method over a wide range of measurement geometries by constructing a series of evolving SAM prototypes. Field tests have been conducted in a variety of water types ranging from highly turbid water with suspended sediments in Narragansett Bay to very clear water of Lake Tahoe, comparable to the oligotrophic ocean. All measurements are taken with co-occurring ac9 data for calibration and validation. These empirical data from lab and field efforts complement our theoretical analyses, and have allowed us to constrain the geometrical parameters of the final prototypes.

Our approach to deploying the SAM in an AUV platform has been to work in collaboration with Webb Research Corp, the Rutgers University glider team, and Metron to integrate a SAM and other miniaturized optical sensors into a Slocum glider. Working with this experienced team has ensured the effective collection and transmission of SAM data and provided a direct link for its use in the Navy applications it was designed to support.

A goal of this work is to use the full suite of measurements made with the glider sensor package to derive a basic set of IOPs, including total attenuation, total scattering, total absorption, and backscattering. To accomplish this, we are using these measurements in concert with conventional instrumentation such as an ac9 to develop the necessary semi-empirical algorithms.

WORK COMPLETED

The primary experimental work evaluating the various possible SAM geometries was conducted with the SAM test bed (alpha-prototype). This prototype had an adjustable source angle, detector field-of-views (FOVs), and flexibility in positioning between the source and two detectors along a rail support. Maalox and milk were primarily used as scattering agents in the lab, as these solutions represent a wide range of VSF shapes (wider than observed naturally) – from Rayleigh-type phase functions (milk) to more ocean-like (Maalox).

Based on results with the alpha-prototype, three beta SAMs suitable for integration with a Slocum glider were designed and produced (**Fig. 1**). FOVs for these sensors are 3.6 degrees and the source angle is adjustable between about 30 and 40 degrees. The detectors are separated by 12 cm. Three sets of two WET Labs ECO style sensors compatible with a Slocum glider were also designed and produced. These sensors are the BB2C and BB-LSS, measuring $\beta(532,117°)$, $\beta(650,117°)$, $\beta(880,117°)$, CDOM fluorescence, and broad-band side-scatter.

Two glider SAMs and two sets of optical ECO sensors were integrated into two Slocum gliders. In collaboration with Clayton Jones' group at Webb Research Corp., a glider sensor payload compartment was designed and form factors were matched. Electronic and communications integration was facilitated.

Deployments for testing and characterizing the glider SAM and associated glider ECO sensors have been conducted in Lake Tahoe, Narragansett Bay, Buzzards Bay, the New Jersey coast, and the Virginia coast. For the latter three sites, the sensors were deployed autonomously with the Slocum glider in collaboration with the Rutgers glider team headed by Oscar Schofield. The SAM was calibrated vicariously with an ac9 that was deployed nearby as part of a vertical profiling package. Glider SAM data from the recent CBLAST exercise has been processed and analyzed. From the attenuation values, diver visibility estimates have also been computed using the algorithm developed by Ron Zaneveld and Scott Pegau. Work progresses on processing and analysis of glider SAM data from recent MIREM exercise off the Virginia coast.

A plan was developed for how SAM data and other optical data from the glider will be incorporated into models to predict lidar MCM system performance. Processed data from the C-BLAST exercise has been transferred to our collaborators at Metron (T. Stefanick) to support this effort.

A starting template for algorithm development work was established and subsequent work has proceeded with the field data, both recently collected and historical.

Recently, a second generation glider SAM was designed and constructed that incorporates a beam expander to increase sample volumes. Testing begins in early October 2003.

Figure 1. ***The beta prototype SAM, compatible with AUVs including the Slocum glider. For deployment on the glider, the sensor face is removed from the housing and then seated into the glider payload compartment.***

RESULTS

Alpha-prototype results were as follows. As predicted from theory and modeling, 1) the relationship between c(650) and ln(β1/β2) was highly linear for the hydrosols and geometries tested, 2) the resolving capability of the method was improved by narrowing the FOVs of the detectors, and 3) VSF dependencies of the method were reduced by narrowing the FOVs and decreasing the source angle (between laser and sensor face). These primary results formed the basis of the final geometry stipulated for the glider SAMs.

The first deployment of a glider SAM was in Lake Tahoe in May, 2003 on a profiling cage. The SAM performed well in Tahoe, demonstrating linearity with respect to attenuation and predictive capability at the 0.1 1/m level. The Tahoe exercise also provided our first exposure to issues such as how to incorporate dark counts into the calibration algorithm. Further deployments in Narragansett Bay and other sites helped tackle these issues and develop a calibration protocol.

Results from the SAM deployed on the glider have been promising. **Figure 2** shows the good agreement between a profile of attenuation collected with the glider in Buzzards Bay, MA during the CBLAST exercise and a profile collected with an ac9 on a nearby ship deployed profiler. **Figure 3** shows an example of interpolated SAM attenuation data from one of the glider transects during this exercise. These types of maps of attenuation are the inputs for models that compute lidar performance and diver visibility. Calculations of diver visibility for this transect based on the algorithm developed by Zaneveld and Pegau (2003) estimated visibilities of 2 m at the bottom and about 7 m in the surface 8 m (see Zaneveld and Pegau Final Report for interpolated image).

In the IOP algorithm development work, the $c_{pg}(532) - c_{pg}(650)$ relationship has shown a striking agreement with the results of Barnard et al. (1998), where the best fit slope matches at a value of 1.11. Preliminary analyses of the slope of the backscattering spectra and attenuation spectra have shown a correlative relationship and the potential for exploiting this to better estimate c(532) from c(650) is under investigation. Other algorithm development work is in progress.

IMPACT/APPLICATIONS

Progress and results represent important steps toward the development of a compact, flat face beam attenuation meter for Naval operations and oceanographic research. Naval applications for the SAM include predicting performance of lidar MCM systems, and for estimating diver visibility and vulnerability. Oceanographic research applications include estimating type and concentration of suspended particles, generalized size distribution of particles, evaluating the various components of seawater that attenuate light, and water clarity.

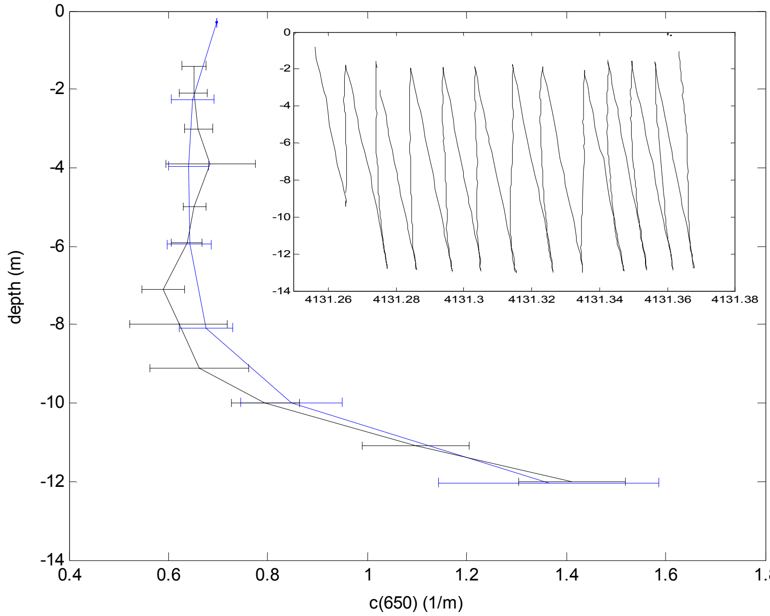

Figure 2. ***SAM data in blue, ac9 in black. Average and standard deviation are shown. Glider flight path inset. All glider SAM data from transect used in binning for this analysis. Estimates of attenuation with SAM and ac9 show a strong agreement in both magnitude and standard deviation.***

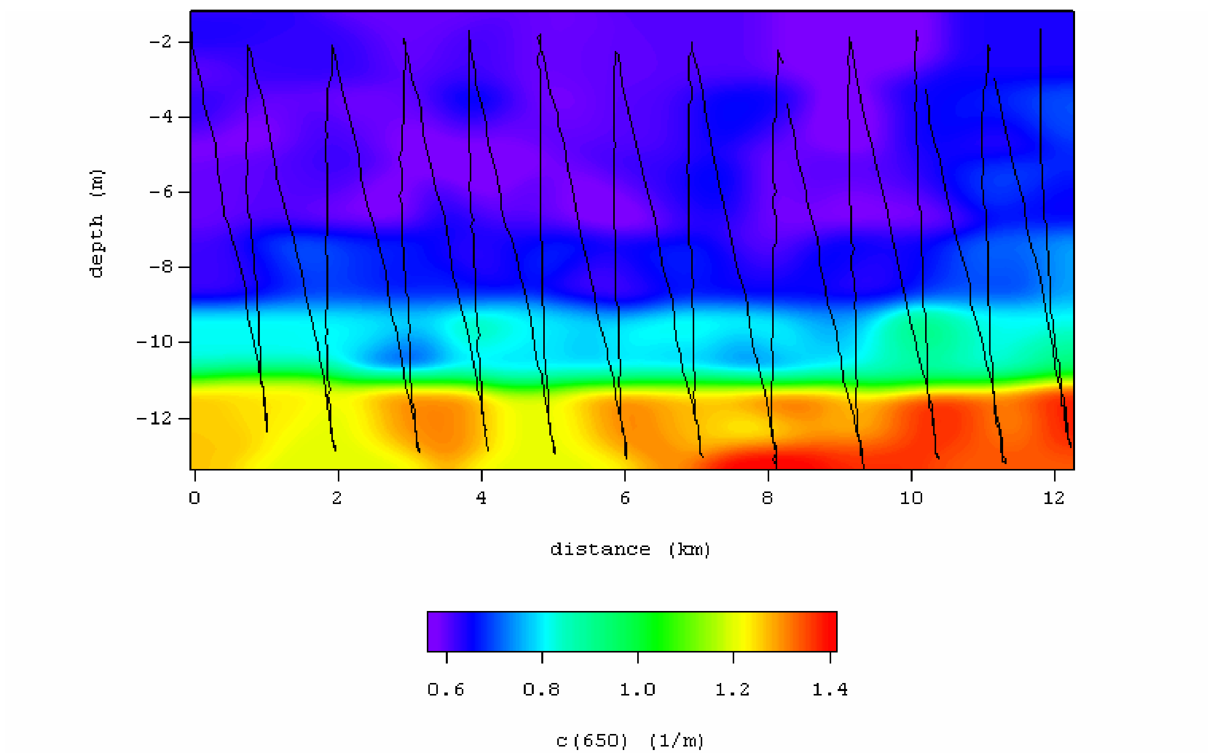

Figure 3. ***Interpolated transect of beam attenuation at 650 nm collected autonomously with a SAM on a Slocum glider. Glider track is superimposed. Attenuation values range from 0.6 to 1.4 1/m and a bottom nepheloid layer is prominent.***

TRANSITIONS

We anticipate work culminating in the successful integration of the SAM on a Slocum glider will be of value in future efforts integrating the SAM on other automated platforms such as REMUS vehicles, Bluefin vehicles, APEX floats, the Seaglider, underwater profilers, and moorings. Contacts have been made in planning these efforts with the manufacturers and research groups involved in developing and deploying these platforms.

Through the Slocum glider effort, we have been working with the Naval Oceanographic Office and Navy fleet personnel to demonstrate the capabilities of the SAM sensor deployed on the glider. We expect that these interactions will be helpful in facilitating an efficient transition of the SAM and glider technology into the fleet in the future.

The technological advances made with the development of the SAM are being used to develop an integrated, miniaturized bio-optical sensing package, with development hitting full swing by January, 2004.

We anticipate results from the SAM deployed on a glider will be presented at Ocean Optics XVII (2004), and a manuscript on this work is in preparation.

RELATED PROJECTS

Our efforts with SAM are collaborative with a R. Zaneveld and S. Pegau visibility study (ONR). Alan Weidemann (NRL) is also involved in testing the optical sensors used on the Slocum glider, including the SAM. The SAM is pertinent to ongoing work investigating the relationship between IOPs and biogeochemical properties, involving Ian Walsh (WET Labs) and David Murray (Brown U.). The SAM is also relevant and a potential tool in several ongoing projects concerned with deploying sensors on compact, remote sampling platforms. These projects include MOSEANS (NOPP, T. Dickey, UCSB), the Virtual Mooring Glider (NOPP, M.J. Perry, U. Maine), and the Ocean Response Coastal Analysis System (remote profilers, NOPP, P. Donaghay, URI). Andrew Barndard is also spearheading an effort to adapt the SAM for use as part of ocean observing systems currently under development at WET Labs.

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PATENTS

Scattering attenuation meter (SAM).

HONORS/AWARDS/PRIZES

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M. Twardowski, WET Labs, ASEE Fellow, ASEE, 2000.